RESEARCH ARTICLE

Development and Experimental Performance Evaluation of a Multifunctional Refrigerator for Food Preservation

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ABSTRACT: A multifunctional refrigerator for heating and cooling of food has been designed, tested and presented in this work. It is a more viable alternative means of keeping food warmth before consumption rather than using the conventional microwave oven. The waste energy from the refrigerator is harnessed and routed to a heating chamber where it is used to heat up processed food materials. The system was built using stainless steel sheets, fibres, and a small fan as well as the compressor, evaporator and expansion valves of a conventional vapour absorption refrigeration system. It has both refrigerating and heating compartments. The topping heating compartment receives heat from the condenser through air circulated in a tube around it. Series of tests were carried out on the system to monitor the temperatures of both the heating and cooling chambers. Results obtained show that the system, apart from performing its function as a refrigerator, can also be used as an alternative to the conventional Microwave Oven as temperatures as high as 60°C was achieved in the heating compartment and as low as 14°C in the cooling compartment. Also, the COP of the system is improved by about 6.5%.

KEYWORDS: Multifunctional; Refrigeration; Microwave Oven; Heating and Cooling; Food Preservation; Sustainability

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1. INTRODUCTION

Increasing energy cost issues on the global scale, energy security, and the ensuing environmental concerns from the emissions inherent in conventional energy sources have led to the search for viable alternatives and the most efficient means of utilizing the available energy. This has made waste heat recovery from thermodynamic systems a field of utmost interest in recent times as one of the means of energy conservation measures [1]. Refrigerators are cooling appliances comprising thermally insulated compartments and designed with features to maintain items in the cooling compartment below room temperature. They are extensively used to store foods, avoid spoilage from microbial activities; keep vegetables and fruits fresh until time for use, and other preservative measures requiring low temperatures. They commonly have two prime components, involving energy transport, namely, the evaporator and the condenser. While the evaporator is a heat exchanger that extracts heat from the items in the refrigerating space to keep them cold, the condenser, another heat exchanger conveys the extracted heat at a higher temperature to the ambient environment. Cooling in this system is accomplished through the gain or loss of latent heat of vaporization of a liquid refrigerant under varying temperatures and pressure.[2] estimated that there are well above one billion units of household refrigerators worldwide and this means the increased burden on global energy consumption as well as an increased amount of waste heat from the system which invariably will impact heavily on the environmental ecosystem. A significant amount of heat energy is rejected by the refrigerator condenser as waste heat[3, 4].

Primarily because the device is mainly designed for maximizing the refrigerating (cold) space, the heat energy harnessed in the condenser is not normally utilized in the process. Several concerns have been raised concerning the effect of the rejected heat from the condenser of the refrigerator on the

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environment [5] patented a work (US patent),multipurpose warming apparatus which was heated by the waste heat from the condenser of a refrigerator for such household activities as food warming and curd making. The chamber recorded a maximum temperature of 50°C, with an average temperature of 40°C, which are highly sufficient for most of domestic food warming applications. Also, [6] modified a household refrigerator to keep food cool and provide hot water at the condenser side by replacing the condenser with a spiral heat exchanger immersed in water to heat it as the refrigerator is working. He reported a water temperature of 60^{o}C and the coefficient of performance of the dual unit as 7, comprising 3 on the refrigerating side and 4 on the thermal side [7] designed and constructed a dual-purpose household refrigeration system for both air conditioning and refrigeration purposes. Their system is a split configuration consisting of indoor and outdoor units, comprising a single compressor, condenser, and two evaporator coils controlled by solenoid valves to allow the functioning of the system as independent refrigerating or air conditioning units, or simultaneous functioning of the refrigerating and air conditioning units. However, the waste energy at the condensing unit was not harnessed for alternative use.[8] in a case study of waste heat recovery from a domestic refrigerator found out that household refrigerators not only can preserve foods at temperatures below 4^{o}C but also can provide waste heat from the condenser that can heat water up to 55^{o}C for domestic activities [9] recorded a temperature of 45^{o}C at the condenser side of a household refrigerator when heat harnessed from the condenser was utilized to heat water for domestic activities. It has been commonly reported that the utilization of waste heat from the refrigerator for varying purposes adds to the economic importance of the system by reducing power consumption and improving the coefficient of performance of the vapour compression refrigeration system [3, 4, 8, 9, 10, 11, 12]

Sami et al., [13] have opined that this heat contributes to environmental degradation and suggested its exploitation to meet some heating needs. They modified a household refrigerator to perform the dual function of cooling food items and heating water at the condenser unit, by immersing the condenser compartment in water in order to channel the waste heat from the refrigerator into heating the water. However, their primary concentration was on the determination of the optimum condenser length for the best coefficient of performance of the refrigerating unit [1] designed and constructed a dual-purpose household refrigerator with a drying compartment for drying fabrics in the tropics. They retrofitted the condenser unit of the refrigerator to recover the waste heat and channel it to another compartment in the unit referred to as the drying compartment. The drying chamber attained a temperature of 49^{o}C in a pre-loading test conducted while the cooling compartment reached an all-time low of 5^{o}C. The system thermodynamic performance was not hampered as the coefficient of performance was recorded to be 10.09 and they posited that the energy given out by the hybrid unit was 10 times higher than what it consumed.

Qualities of food items (processed or raw) can be preserved through thought-out treatment techniques in order to extend the shelf life or freshness period. This has become a lingering challenge not only to food industries but also to households [14]. Microwave heating is one of the new technologies for food quality conservation due largely to its rapid heating and high energy efficiency. It can provide rapid heating of food for consumption in a short range of time. Furthermore, it is also used for drying and preservation of foodstuffs that need to be moisture-free to ensure they have a longer shelf life. However, microwave ovens operate on microwaves which are high-frequency radio waves (RF), and as visible radiation, it is part of the electromagnetic spectrum. Microwaves have three characteristics that allow them to be used in cooking, namely, they are reflected by metals; they penetrate through glass, paper, plastic, and similar materials; and they are absorbed by foods [15].It has been reported that microwave radiation can heat body tissues the same way it heats food. The human body absorbs high-frequency radio waves and converts them to heat [16].Even though not much is reported about the health effect of exposure to low microwave radiation, exposure to high levels of microwave can cause skin burns or cataracts [17]. In the event that the oven door hinges, latches, or seals are damaged or the door is not properly closed, the microwave energy can leak from the oven, posing serious health issues. Also, non-uniform temperature distribution occurs during microwave heating of food materials [18]; and this non-uniform temperature phenomenon in the different

layers of the food item results in the formation of a large amount of acrylamide (which is a neurotoxin and carcinogenic substance discovered in food in recent times) [19]. Therefore, microwave heating specifically favours low-specific heat food materials [19, 20]. Michalak et al., [19] have reported noticeable difficulty in the control of household microwave ovens, unlike their industrial counterparts. If not well controlled, the formation of harmful compounds like acrylamide can be excessive.

From the foregoing, superheat recovery from the refrigerator has been predominantly applied for water heating. Application for food warming and fermentation for yeast formation for bread and pizza making has not received wide attention. Nowadays, households are increasingly acquiring refrigerators and microwave ovens for food preservation and heating purposes. These devices independently consume a significant amount of electrical energy and invariably increase household energy bills. Also, the neurotoxic and carcinogenic substances discovered in foods heated by microwaves have become of great concern. The present study is, therefore, focused on exploiting the refrigerator superheat (waste heat from the condenser) and recycling the same to heat up an insulated chamber on top of the cooling compartment for simultaneous food warming before consumption. This will lead to significant energy savings, preservation of health, and environmental safety.

2. *System configuration and description*

The configuration of the multifunctional refrigerator is as shown in Fig. 1a. The charge valve introduces the refrigerant into the compressor, where it is compressed and lets into the condenser. The condenser is made of copper wires coiled into a spiral shape for increased heat absorption from the refrigerant to more heat available to the heating compartment. The evaporator is an aluminium sheet with a coiled pipe pathway coated white. The cold refrigerant passing through the evaporator coils absorbs the latent heat from the items in the cold chamber and boils. The expansion valve is connected between the condenser and the evaporator to expand the refrigerant inside. It is assumed that the expansion process is isenthalpic, the compression process is isentropic, and there is no irreversibility in the condenser, evaporator, and compressor while frictional pressure drops are minimal. The refrigerant used is R134a due to its zero Ozone Depletion and low Global Warming Potential of 1300 and normal boiling point of 4.67^{o}C. The refrigerant on passing through the condenser and the evaporator become moisturized. The drier positioned at the exit of the evaporator helps in keeping the refrigerant moisture free before going into the compressor. A well thermally insulated aluminium sheet is wound around the condenser like a hollow ring and together forms an improvised heat exchanger, and an axial fan positioned around the condenser coil blows the waste heat from the integrated heat exchanger into the heating chamber of the hybrid refrigerator as shown in the figure. The speed of the fan ranges between 2400 – 3000 rpm. All the aluminium sheets were joined together with riveted brass. Fig. 1b shows the complete assembly of the system. The whole assembly was also well thermally insulated to avoid leakages and thermal losses.

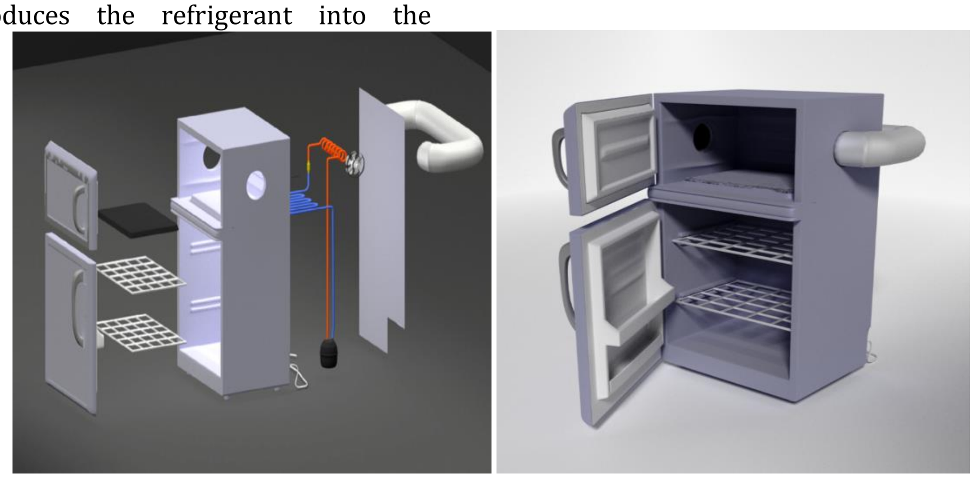

Fig 1:(a) Exploded view **(b) Complete System Assembly**

3. *System sizing*

The conventional Vapor Compression Refrigeration System (VCRS) as shown in Fig 2a is adopted and retrofitted to suit multipurpose use as shown in Fig 2b. Fig 3 is a thermodynamic diagram of the VCRS process [1]. Process 1-2 is the compression of the refrigerant (vapour) at low pressure; process 2-3' is the condensation of the high-pressure refrigerant at vapour phase to high-pressure liquid; process 3'-4 is expanding liquid refrigerant at high pressure to supercooled liquid at low pressure, while process 4-1 is the evaporation of the liquid refrigerant to the vapour phase at low pressure [1,3].The condensation process comprises three sub-processes, namely, de-superheating (2-2'), condensation, and sub-cooling [3]. In the process of evaporation, heat is absorbed by the refrigerant, which is rejected to the ambient during condensation. This heat is waste heat to be recovered for useful heating or food warming purposes through an improvised heat exchanger.

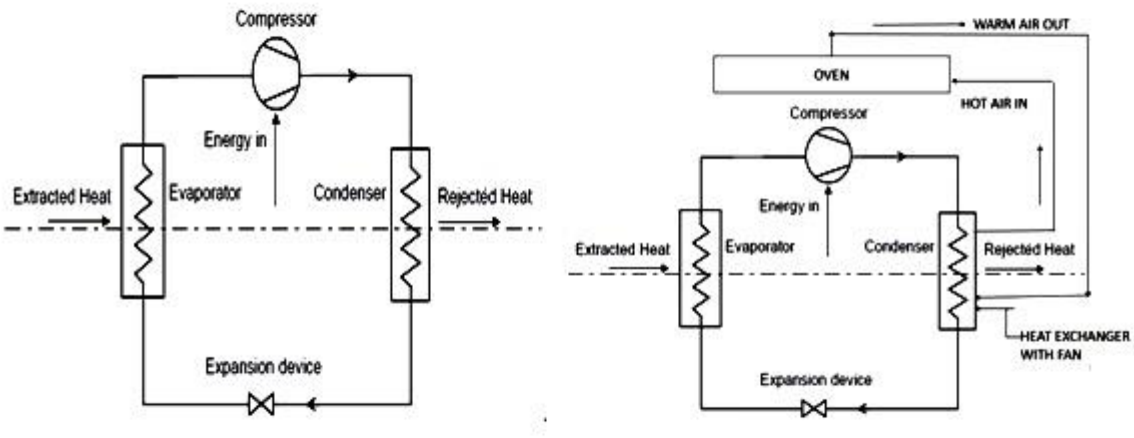

Fig 2: (a) Conventional VCRS **(b) Retrofitted VCRS for waste heat recovery**

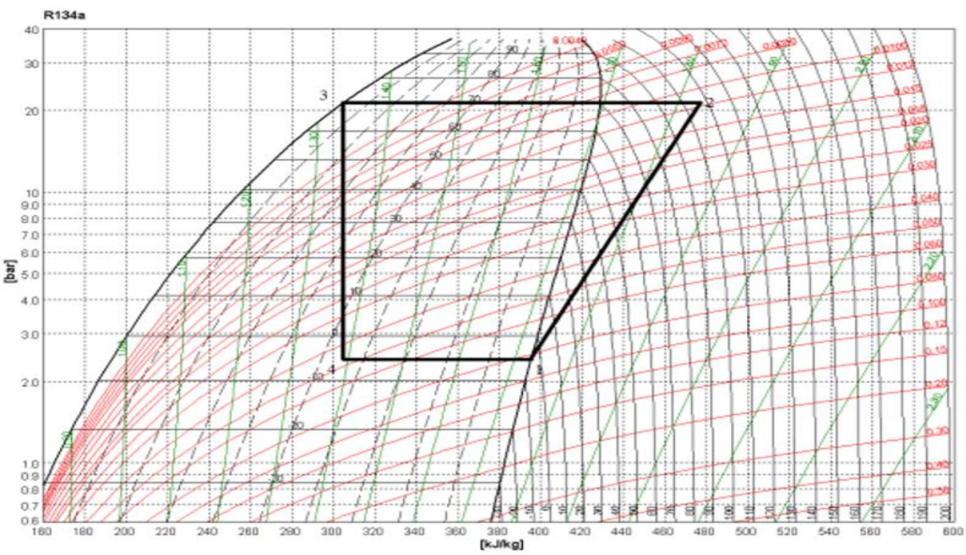

Fig 3: Pressure-enthalpy diagram of R134a refrigerant[8]

3.1 *System mass flow rate, cooling and heating loads estimation*

The refrigerator of choice for this study is a hermetic refrigerator with a compressor of 1/12 HP nominal power, R134a refrigerant, rated power of 62W/78W, and cooling capacity of 65/78. The mass flow rate of the R134a refrigerant, and the cooling and heating loads of the cooling and heating compartments are estimated following ASHRAE-approved procedures.

The refrigerating effect or heat absorbed by the refrigerator is given as the mass rate of flow

of the refrigerant. The mass flow rate, therefore, is given as:

$$\dot{m} = \frac{Coolingloadoftherefrigeratingspace}{h_{1-4}} \quad (1)$$

Where h_{1-4} is the net enthalpy between the inlet and outlet to the evaporator, represented by points 1 and 4 in Fig. 3.

From the pressure-enthalpy diagram (Fig. 3) for R134a, enthalpy values at state points 1, 2, 3, 4 are $h_1 = 395\,kJ/kg$,$h_2 = 468kJ/kg, h_3 = 305kJ/kgandh_4 = 305kJ/kg$, respectively.

Therefore, the mass flow rate,

$$\dot{m} = \frac{78}{(395-305)x1000} kg/s$$

$$\therefore \dot{m} = 0.052kg/min$$

The compressor work can now be calculated as:

$$W_{1-2} = h_{1-2} * \dot{m} \quad (2)$$

Here, h_{1-2} is the enthalpy difference between points 1 and 2 in Fig. 3, which provides the isentropic heat during compression.

$$W_{1-2} = (468 - 395)x1000J/kg * 0.052kg/min$$

$$\therefore W_{1-2} = 63.29W$$

The refrigerant effective mass flow rate is given as:

$$\dot{m}_{eff} = \frac{W_{1-2}}{h_{1'-2}} \quad (3)$$

The effective cooling load is expressed as:

$$CoolingLoad_{eff} = \dot{m}_{eff} xRefrigerationEffect = \frac{W_{1-2}}{h_{1'-2}} \quad (4)$$

$$CoolingLoad_{eff} = \frac{W_{1-2}}{h_{1'-2}} xRefrigerationEffect \quad (5)$$

$$CoolingLoad_{eff} = \frac{W_{1-2}}{h_{1'-2}} xh_{1-4} \quad (6)$$

The net refrigerant effect is estimated at 78 kJ/kg.

The system coefficient of performance can be calculated from:

$$COP = \frac{RefrigerantEffect}{h_{1-2}} \quad (7)$$

$$COP = \frac{78}{73} = 1.07$$

The heat of condensation, given by h_{2-3}, is obtained from the difference in enthalpy between points 2 and 3 in Fig 3. That is,

$$h_{2-3} = h_2 - h_3 \quad (8)$$

This heat of condensation is calculated as 163 kJ/kg.

The heat dissipated by the condenser is expressed as:

$$Q_{2-3} = h_{2-3} x\dot{m}_{eff} \quad (9)$$

The effective mass flow rate is the term otherwise known as the tonne of refrigeration expressed in kg/min. It is estimated at 141.27W. For a heat exchanger effectiveness of 75%, this heat becomes 105.95W.

Now, the amount of heat required to raise the air temperature in the heating chamber is given as,

$$Q_a = \dot{m}_a c_{pa} \Delta T \quad (10)$$

Where $\dot{m}_a$ is the mass flow rate of air, c_{pa} is the specific heat capacity of air and ΔT is the temperature difference between the air at inlet condition and that at outlet condition.

The amount of time required to heat the item in the heating chamber is, therefore, given as:

$$t = \frac{Q_a}{Q_{2-3}x60} \text{ (min)} \quad (11)$$

It would require about 13 minutes to add heat to the food item in the heating chamber to make it warm.

For an estimated heating time of 100 minutes to raise the heating chamber from 33^{o}C to 60^{o}C, 1 kg of air would absorb some amount heat. This heat would then become the heat recovered in the system, given as:

$$Q_{absorbed/recovered} = m_a c_{pa} \frac{\Delta T}{\Delta t} \quad (12)$$

From Eq. 12, a total amount of 4.52J/s was recovered.

Since the waste heat from the condenser is utilized to provide heat for the hot chamber compartment, the coefficient of performance of the system is expected to improve by a certain

amount. The COP enhancement can be calculated as given in Eq. 13[12]:

$$COP_{enhanced} = \frac{RefrigeratingEffect}{W_{1-2} - Q_{absorbed/recovered}} \quad (13)$$

$$COP_{enhanced} = \frac{78}{73-4.52} = 1.14$$

Therefore, about 6.5% improvement in COP of the refrigerator is achieved by extracting heat from the absorber to warm food items in a separate compartment incorporated in the refrigerating system. Table 1 shows the specifications of the components of the multifunctional refrigerator.

Table 1. Dimensions of some key components

S/N	Component	Parameters	Dimension
1	Condenser	Length of tube	7.0m
		Diameter	1.5×10^{-3}m
2	Evaporator	Length of tube	6.0m
		Diameter	1.5×10^{-3}m
3	Capillary tube	Length	3.35m
		Diameter	0.8×10^{-3}m

3.2 Other Possible Applications and Operational Safety

As have been pointed out by [1,12], the multifunctional refrigerator, apart from providing the primary function of food preservation and warming, can also be employed for fabric drying, water heating for domestic activities and other activities such as bathing in schools and hospitals as well as sterilization of medical instruments requiring 50-55°C. With the use of higher compressor ratings and highly efficient heat exchangers, greater quantity of heat can be harnessed from the condenser to carry out other activities requiring temperatures above 60°C. However, safety issues arise when it concerns retrofitting for food warming. The cooling and heating chambers should be properly insulated to make them air-tight and avoid refrigerant leakage into them. Also, the filter dryer-condenser joint should be well sealed to avoid refrigerant leakage while the system is in operation, as this would lead to system malfunctioning, with obvious results of not being able to produce heat or cool any food item placed in the chambers.

4. RESULTS AND DISCUSSION

The results of field tests conducted in the retrofitted refrigerator incorporating a heating compartment for warming of food before consumption are presented in Figs 4-7.

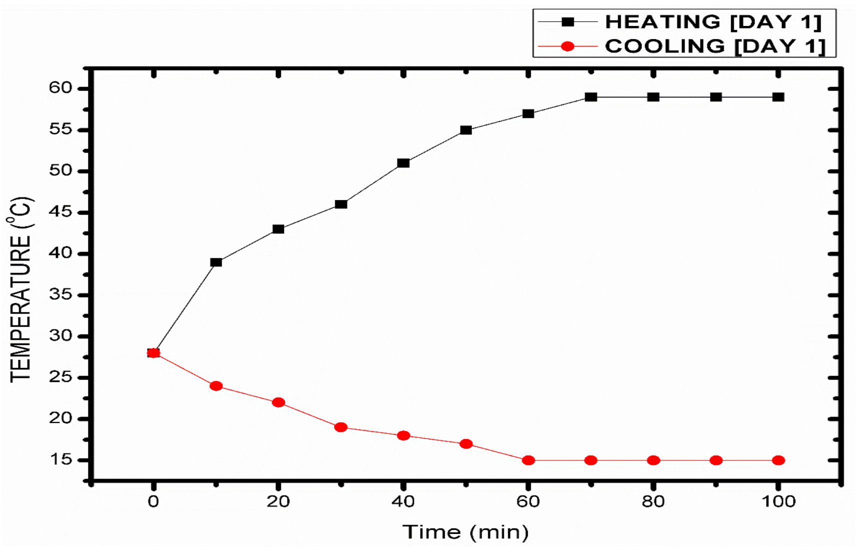

Fig 4: Temperature variations in the cooling and heating compartments during day one test

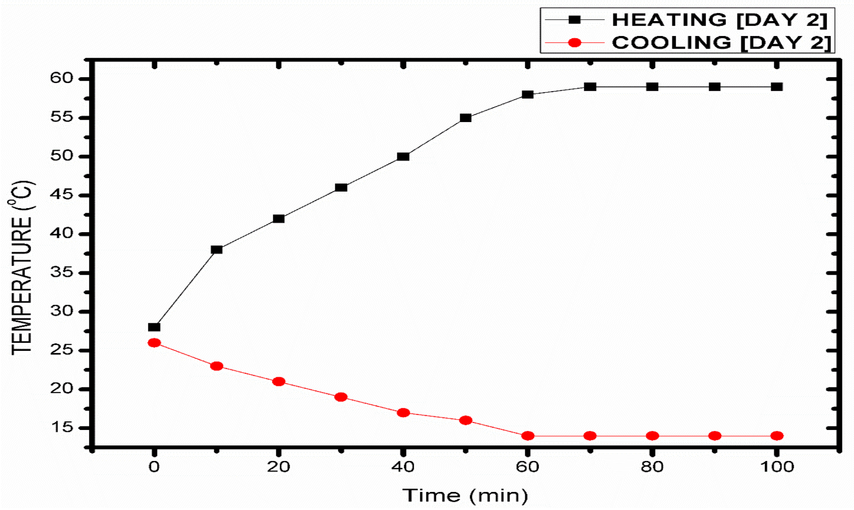

Fig 5: Temperature variations in the cooling and heating compartments during day two test

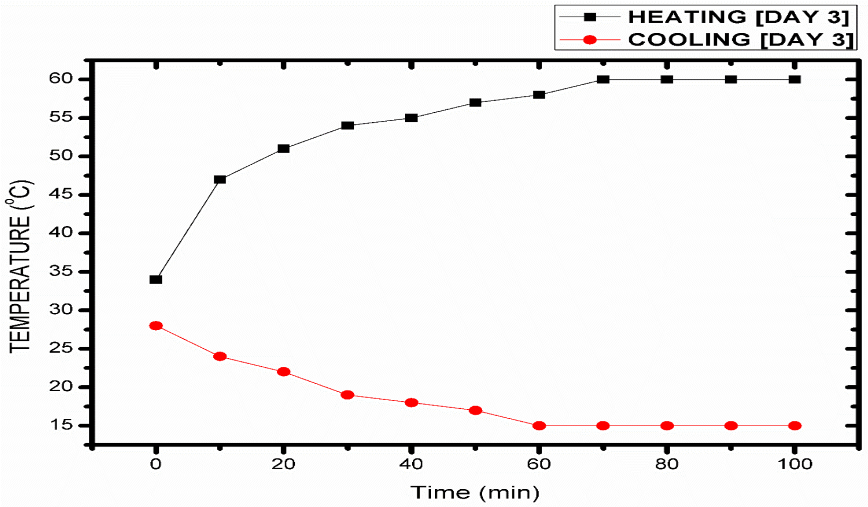

Fig 6: Temperature variations in the cooling and heating compartments during day three test.

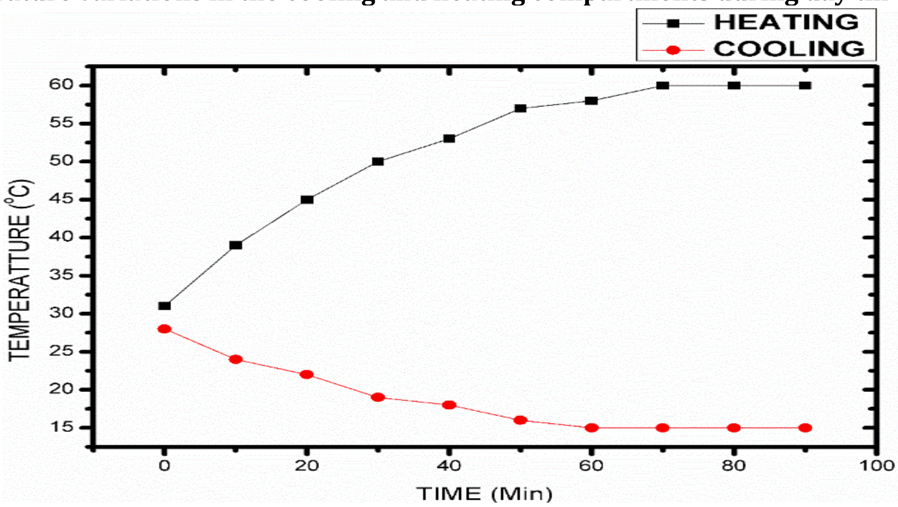

Fig 7: Temperature variations in the cooling and heating compartments during day four test.

The temperatures of both the cooling and heating compartments were monitored every ten minutes intervals throughout the days the tests were conducted, using a k-type digital thermometer. On the first day of the test, as shown in Fig. 4., observable temperature reduction and increment were recorded in both the refrigeration space (cooling compartment) and oven space (heating compartment). The temperature of the heating compartment

increased progressively from 28°C to about 60°C in a period of 70 minutes. Thereafter, it maintained this value of 60°C throughout the period of the test. This heat harnessed in the heating compartment is the heat from condenser unit of the system. Also, the cooling compartment decreased progressively from 28°C to about 14°C in 60 minutes and maintained this uniform value throughout the test. The fan attached to the improvised heat exchanger was on throughout the period of the test and that was to ensure that the hot air from the condenser unit was constantly channeled into the heating chamber. From Fig. 5, it can be observed that both cooling and heating chambers attained their minimum and maximum temperatures at the simultaneously, at about 60 minutes from the commencement of the operations. The other days tests as depicted in Figs 6 and 7 exhibited the same pattern as they attained maximum heating temperature 70 minutes after commencement the tests and minimum temperatures 60 minutes after test commencement.

From the test runs conducted for four different days at the duration of 100 minutes and 10 minutes intervals, it can be seen that using the smallest compressor 1/12HP, a maximum temperature of 60°C and a minimum of 14°C were attained, though at different times, but were maintained for the rest of the test duration. Onyeocha et al [1], in a six-hour test run on a hybrid refrigerator with fabric dryer compartment, reported that in 2 hours 30 minutes (i.e., 150 minutes), the fabric dried up while the refrigerating space attained a temperature of 12°C. This confirms reports from previous works that the system can be used for both heating and cooling purposes at the same time.

5. CONCLUSION

A multifunctional refrigerator incorporating a food warming chamber atop the refrigerating space has been developed. This was done by retrofitting an existing conventional refrigerator with 1/12 HP compressor. A heat exchanger was improvised to harness the condenser heat and channeled into the heating chamber by a fan. From a test run carried out for four consecutive days, the heating chamber attained a maximum temperature of 60°C while the cooling space attained a temperature of 14°C at an average period of 65 minutes. The COP of the system is improved by about 6.5%. Having such a multifunctional system in our world today is a very excellent innovation, as it possesses a whole lot of economic, health, social and environmental benefits. It is considered the best alternative for more cost-effective food preservation, implementing both heating and cooling using one system, instead of having to purchase two different devices, namely, microwave oven and refrigerator. It is recommended that for further research on the system, higher compressor ratings such as 1/10, 1/8, 1/6, 1/4, 1/2 and 1HP should be employed to investigate the performance of the hybrid system. This is because with higher compressor rating, a greater heating level can be attained at constant diameter of the condenser. Also, employing refrigerants with higher heat capacities can help generate greater levels of heating and cooling at the corresponding chambers.

Acknowledgments

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